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SUMMARY

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2. BACKGROUND.
Author: G. Andersen

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Large holographically corrected imaging and nulling interferometers

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Abstract
Presented here is a method for the correction of large, inexpensive sparse telescope arrays over a narrow bandwidth. A hologram is created of the distributed primary which is capable of correcting for thousands of waves of random and geometrical errors while simultaneously compensating for phasing errors. Experimental results are presented that demonstrate the application of this technique to meter-class, six-segment imaging interferometers as well as a two-mirror nulling interferometer.
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Introduction

Launch vehicles currently limit the diameter of a monolithic primary mirror to around 4m, while engineering issues may end up limiting the diameter of segmented primaries to around 10m. Sparse aperture telescopes are an alternate method for obtaining high resolution imaging without the requirement of large filled primaries. These may be either rigidly attached or free-flying apertures which are then phased together *in situ*. Even with a static configuration, the light from each aperture must be combined (phased) using a number of precisely tuned delay lines – something which is difficult enough in a stable and controlled environment on Earth[1-5]. Holographic correction has been widely demonstrated as a method for correcting large aberrations in monolithic optical elements over a narrow bandwidth[6-11]. Here this concept is extended to use of multiple low quality mirrors of any conic to be used in a sparse array – an approach that leads to a large amount of flexibility in mission designs and concepts while also reducing their costs.

Holographic phased array

The process of holographic correction begins with a distant source of laser light (the beacon) illuminating the primary (Fig 1(a)). The reflected, focused light is then directed through a secondary that produces a demagnified image of the primary onto a holographic medium (e.g. film). A hologram is created by recording the interference pattern between this object beam and a coherent, diffraction limited reference beam incident on the medium from an angle. On reconstruction Fig 1(b), light from a distant source is incident on the aberrated primary. The reflected light passes through the optical system to reconstruct the original reference beam at the hologram. If the source light is that from a distant object, the reconstructed beam will retain the object information making it possible to produce a diffraction limited image. By this process it is possible to remove a large amount of wavefront aberration in a large primary with a small, inexpensive hologram over a limited bandwidth.
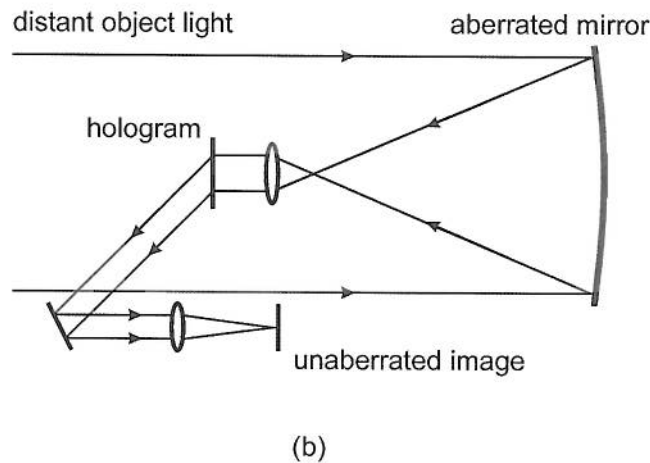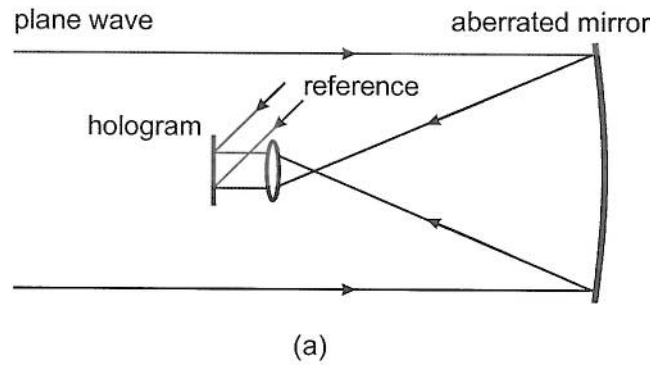
plane wave   aberrated mirror

reference

hologram

(a)

distant object light   aberrated mirror

hologram

unaberrated image

(b)

Fig. 1: (a) A hologram is written using light focused from the aberrated primary and a coherent, diffraction limited reference beam. **(b)** Light from a distant object reflects off the mirror to reconstruct a diffraction limited plane wave and an unaberrated image.

For the purposes of clarity, the description of the holographic correction process given above showed the primary as a monolithic mirror. However, as far as the hologram is concerned there is no requirement for mirror surface continuity. Thus it should possible to use completely independent surfaces from widely separated mirrors so long as they have a static phase relationship. Furthermore, these mirrors need not have matching conics or curvatures, so long as the light is gathered by the secondary. The hologram in this case will correct for all types of phase errors – random surface defects, geometrical errors (e.g. spherical aberration) and phasing errors (piston, tip/tilt) in a single step.
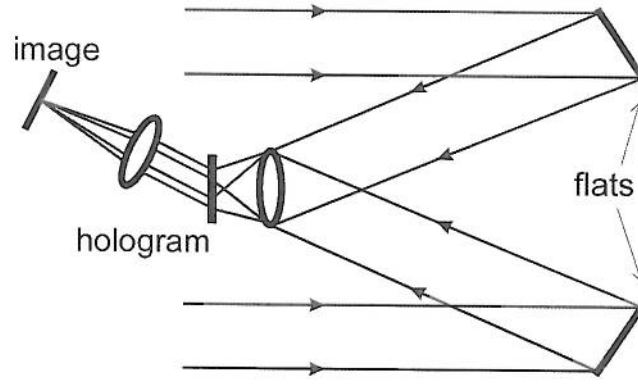
Fig. 2: A schematic of the reconstruction of a multiple mirror array of flats. In this case only two of the six mirrors have been shown for clarity.

The first experimental demonstration used a recording set-up similar to that shown in Fig. 1, with a plane wave produced by a high quality parabolic collimator ($D = 0.983$m, $f = 2.375$m, 0.75λ rms) acting as the beacon. In place of the monolithic mirror we used a combination of six, 76mm diameter flat mirrors arranged in a hexagonal configuration as shown in Fig. 2. The mirrors were arranged around the edge of the collimator aperture with the reflected light gathered by a camera lens ($f = 85$mm, $f/1.2$) located 2.45m away to produce an image hologram 29mm in diameter (Fig. 3(a)). Note that it was not necessary to use flats; they were merely chosen for their lower cost and the fact that it clearly shows that there is no requirement for any particular conics or curvatures. Also, the distances from the flats to the secondary were only matched to with a few millimeters at best which translates into several thousands of waves of piston. Phase transmission holograms were recorded on bleached silver halide plate film using a cw, frequency-doubled Nd:YAG laser ($\lambda = 532$nm) to a typical diffraction efficiency of ~30%.

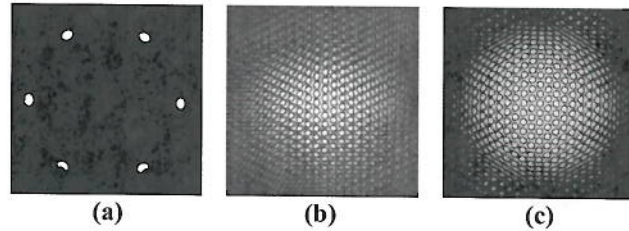(a)   (b)   (c)

Fig. 3: (a) An image of the hologram (aperture function). **(b)** The point spread function of the holographically corrected sparse array. **(c)** A simulated point spread function based on the aperture function shown in **(a)**.

On reconstruction, the multiple object beams reconstructed a single diffracted beam. The point spread function (PSF) of this beam is shown in Fig. 3(b). For comparison, the calculated PSF based on the aperture function of Fig. 3(a) is shown in Fig 3(c). The agreement between the two images indicates that the mirrors are combining in phase. However, the large separation between the mirrors and small fill factor means that this telescope has a very narrow field of view[7,8]. With this in mind, the set-up was modified to that shown in Fig. 4, where the light from the each of six flat mirrors (100mm diameter) was further reflected off a hexagonal arrangement of flats (76mm diameter) located at a distance of 2.44m back to the imaging camera lens located between the first set of flats. The camera lens imaged the second set of flats onto the film to give a hologram around 10mm in diameter.
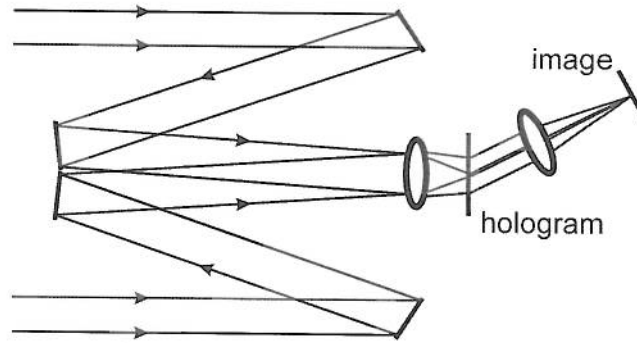
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Fig. 4: Folded array. A hexagonal sparse array of flat mirrors (with only two shown) is reflected off a secondary set of flats, through an imaging lens and onto the hologram.

Once again a hologram was recorded between the multi-aperture object beam and a diffraction limited reference beam. After processing the hologram was returned to the recording position and the diffracted beam analyzed. Fig. 5(a) shows the resultant point spread function which matches that expected from the aperture function. Further evidence of successful phasing is shown in Fig. 5(b) with an interferogram of the reconstructed beam against a diffraction limited plane wave. While two of the mirrors may not be perfectly in phase, the residual error is due to air currents encountered by the large diameter beams over significant path lengths.
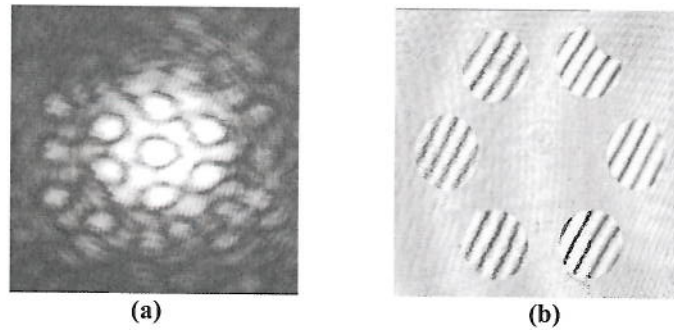

Fig. 5: Reconstruction. **(a)** Point spread function. **(b)** Interferogram. The slight obscuration of the top two mirrors is due to a support structure for the collimator.

Holographic Nulling

The previous two experiments were aimed at combining light from sparse apertures in phase. Another possibility is to combine the light from the mirrors in a deconstructive manner such that an on-axis source is cancelled out. Such a nulling interferometer is useful for planetary studies where the overwhelmingly bright light from a parent star could be attenuated while light from a planet orbiting at some angular separation remains largely unchanged[12-14]. The optical layout for our holographically corrected nulling interferometer is shown in Fig. 6.
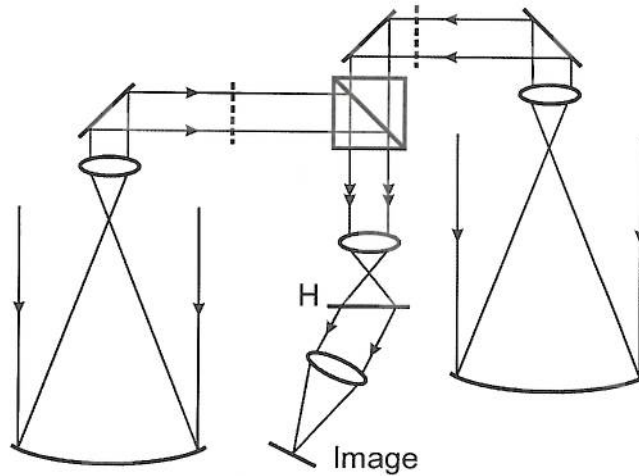
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Fig. 6: Holographically corrected nulling interferometer (reconstruction). Lenses collimate light from spherical mirrors and form an image of each (dashed). These beams are combined with a cube beamsplitter and the image planes are re-imaged onto the hologram (H). The combined object beams reconstruct a plane wave at the hologram.

Two spherical mirrors (D = 194mm, f = 610mm, $\lambda/4$ PV surface error) were separated by 789mm center to center (*i.e.* such that the outer edges touched the edge of the 983mm collimating aperture) and illuminated by a plane wave beacon beam. The reflected, focused light from each mirror (severely distorted by spherical aberration) was then collimated with matching achromat lenses (D = 50mm, f = 150mm). The beams were then combined using a cube beamsplitter such that they were collinear. In this case, some care had to be taken to ensure that the image planes (shown dashed) were the same distance from the beamsplitter. The result was that one of the spherical mirrors had to be set back from the other by a certain amount. A camera lens (f = 85mm, f/1.2) was then used to focus the co-propagating beams and re-image the mirrors onto the holographic film. A phase hologram was recorded with a plane wave reference beam incident on the film at an angle to the object beam in the same manner as described above.

On replay, a plane wave incident on the two mirrors re-created the object beam which is dominated by 23 waves of spherical aberration as shown in Fig. 7(a). At the hologram this beam reconstructed a diffraction limited, plane wave reference beam. Without any change to the set-up, the mirrors combined in phase, giving the bright focus as shown in Fig. 7(b).However, when the angle between these beams was changed slightly (0.2 µrad) the beams were made to combine out of phase as shown in Fig. 7(c). While this experiment serves as a clear demonstration of the possibility of creating a holographically corrected nulling interferometer it was not possible to quantify the depth of the null due to several factors. Firstly the CCD camera only had an 8-bit dynamic range. More importantly however continuously varying air currents throughout the large volume of the experiment continuously imposed changes in relative phasing.
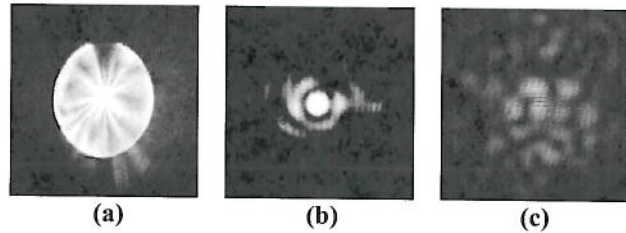

(a)   (b)   (c)

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Fig. 7: (a) The uncorrected focal "spot" showing severe spherical aberration. **(b)** Corrected focus with mirrors combined in phase. **(c)** Corrected nulled focus.

Conclusion

In conclusion, we have experimentally demonstrated the use of holographic correction for meter-class sparse aperture systems. Our first test involved the correction of thousands of waves of random, geometrical and phasing errors in a hexagonal array of flats using only conventional off the shelf optical components. In a second demonstration a nulling interferometer was created using two large spherical mirrors. The success of these experiments indicates a suitability of these approaches to future space-based high resolution surveillance and astronomical telescopes including planet finder missions.

Acknowledgements

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